The Properties of Convective Clouds Over the Western Pacific and Their Relationship to the Environment of Tropical Cyclones

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LONG-TERM GOALS

The long-term goal of the proposed work is to advance our understanding of the relationship between large-scale and mesoscale environmental conditions and small but powerful convective events during tropical cyclone (TC) development and intensity changes. Our ultimate goal is to identify the necessary conditions that determine the formation and evolution of a TC.

OBJECTIVES

With the data obtained during ONR's field program of " Tropical Cyclone Structure 2008 (TCS-08)" over the western Pacific region, the objective of this proposed study is to investigate large-scale environmental conditions, mesoscale phenomena and small scale convective bursts as well as their interactions that are responsible for TC formation and intensity changes. Specific areas include 1) Characterize the intensity of convection over the western Pacific oceans from radar, aircraft and satellite data; 2) Derive an accurate mesoscale environment of convective systems through the assimilation of satellite, radar, lidar and in-situ data; 3) Evaluate the quality of the global forecast system (e.g., Navy Operational Global Atmospheric Prediction System or NOGAPS) for accurate TC analyses and forecasts; 4) Understand the environmental factors that determine tropical cyclone formation and rapid intensification.

APPROACH

In order to achieve the research objectives of this proposal, our approach integrates observational data analysis, mesoscale data assimilation and forecast evaluations. This includes 1) analyzing TCS-08 field data in conjunction with the available satellite data products from Aqua and NASA Tropical Rainfall Measuring Mission (TRMM), 2) developing mesoscale data assimilation techniques to assimilate satellite, radar, lidar and in-situ data into the Weather Research and Forecasting (WRF) and the

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Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS®) mesoscale models, and 3) evaluating the performance of global ensemble forecasting to understand the quality of global forecasts and also study the predictability of TC formation and evolution. People involved in this project include PI (Dr. Zhaoxia Pu), her students (Andrew Snyder, Levi Thatcher, Zhan Li), and a postdoctoral researcher (Dr. Lei Zhang), and NRL collaborators (Drs. Carolyn Reynolds and Allen Zhao).

WORK COMPLETED

Works completed in FY10 include:

(1) Mesoscale numerical simulations of TCS-08 typhoons with assimilation of satellite, radar and in-situ observations

Research activities have been continued on assimilating satellite, radar and in-situ observations for improved numerical simulations of major Typhoons (Jiangmi, Sinlaku, Nuri and Hagupit) during T-PARC/TCS-08 field experiment. The major emphasis was given to 1) airborne Electra Doppler RAdar (ELDORA) data quality control and assimilation and 2) validation of Atmospheric Infrared Sounder (AIRS) retrieved temperature and moisture profiles and their impact on numerical simulations of TCs.

(2) Study the role of vertical wind shear in TC intensity change

Diagnostic studies have been conducted with the high resolution numerical simulation of Supertyphoon Jangmi (2008). The role of vertical wind shear in Jangmi's rapid intensity change was examined. Specifically, two controversial theories (Frank and Retchie 1999 and DeMaria 1996) regarding the role of the vertical wind shear in TC intensity changes were evaluated.

(3) Evaluate the impact of stochastic convection on ensemble forecasts of TC development

Work has continued on comparing two configurations of the Navy Operational Global Atmospheric Prediction System (NOGAPS) ensembles in TC forecasts. Specifically, the impact of stochastic convection on the ensemble forecasts of tropical cyclone development was evaluated.

(4) Investigate the relationship between precipitation characteristics and TC intensity changes

The evolution of precipitation associated with TC genesis and intensification during August –October over the last 10-year (2000-2009) period are statistically characterized in order to investigate the possible relationships between the precipitation evolutions and TC intensity changes. The 3-hourly, real-time merged multi-satellite precipitation products from TRMM and TC best track data from the Joint Typhoon Warning Center (JTWC) are used in this investigation.

RESULTS

(1) *The influence of airborne radar data quality control on numerical simulations of TCs*
The impact of airborne Doppler radar data assimilation on improving numerical simulations of tropical cyclones (TCs) has been well recognized. However, the influence of radar data quality on the numerical simulation of tropical cyclones has not yet been given much attention. In common sense, it

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is assumed that the higher quality of radar data would be more beneficial to numerical simulations of TCs. In collaboration with Dr. Wen-Chau Lee at NCAR and Dr. Qingyun Zhao at NRL, we examined the impact of the radar data quality control on assimilating airborne Doppler radar reflectivity and radial velocity in numerical simulations of Typhoon Jangmi (2008). Specifically, the impact of the radar data quality control on assimilating airborne Doppler radar reflectivity and radial velocity in numerical simulations of Typhoon Jangmi is evaluated. It is found that the quality of radar data has a strong influence on the numerical simulation of Typhoon Jangmi in terms of its track, intensity, and precipitation structures. Specifically, results suggest that a trade-off between the quality and data coverage is necessary in practice, as the high quality data contribute to improved intensity forecast, whereas *lower quality* but better data coverage are more beneficial to accurate track forecasting (Figs. 1 and 2). It is also found that the assimilation of radar data improves the inner core structures of simulated TCs.

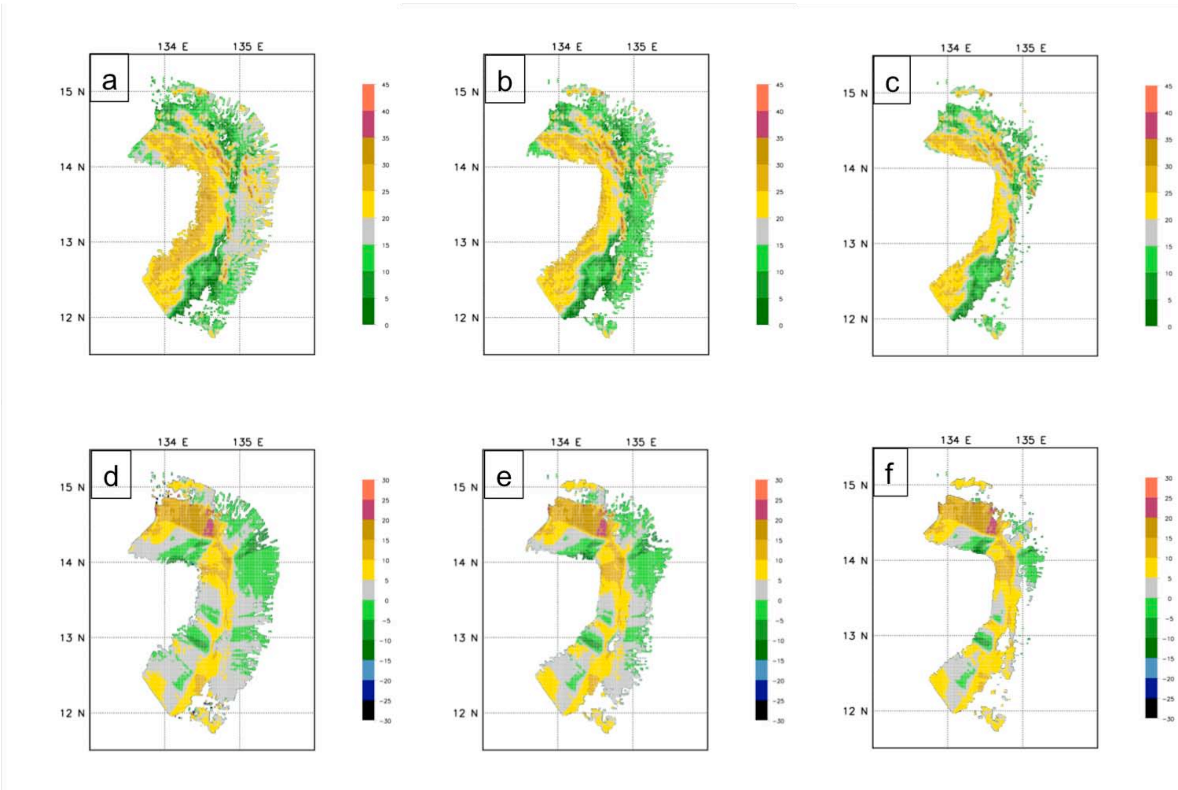

Figure 1. Radar reflectivity (dbz, a-c) and radial velocity (m s^{-1}, d-f) at 0.5 km height level with different quality control (QC) levels around 0000 UTC 25 September 2008. (a) and (d): Low QC level; (b) and (e): Medium QC level; (c) and (f): High QC level.

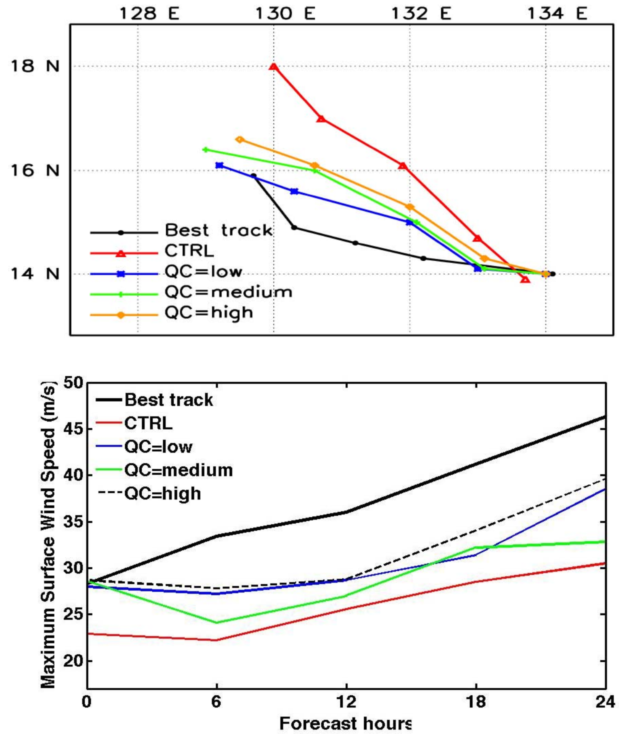

Figure 2. Time evolution of the storm track (top panel) and maximum surface wind (m s^{-1}) (bottom panel) of Typhoon Jangmi from control experiment (CTRL, without assimilation of radar data), experiments with assimilation of both the reflectivity and radial velocity under various quality levels of the data, compared with the JTWC best track data during 0000 UTC 25 to 0000 UTC 26 September 2008.

(2) *Validation of AIRS temperature and moisture profiles over tropical oceans and their impact on numerical simulations of tropical cyclones*

Following the progress last year, the quality of the retrieved temperature and moisture profiles acquired from the AIRS aboard the NASA Aqua spacecraft was evaluated by comparing the data with dropsonde observations obtained from the T-PARC/TCS-08 field programs (2008) and NASA African Monsoon Multidisciplinary Analyses (NMMA) field campaign (2006). Results indicate that the AIRS retrieved temperature profiles are in good agreement with dropsonde observations. However, the AIRS retrieved moisture profiles show a larger bias compared with the dropsondes over the tropical oceans where tropical cyclones developed.

A series of data assimilation experiments were also performed. Results show that the assimilation of the AIRS retrieved temperature and moisture profiles has a significant impact on the numerical simulations of tropical cyclones. However, the overall impacts of the data assimilation on numerical simulations of TCs are very sensitive to the bias corrections of the AIRS retrieved data. Specifically, the dry biases of moisture profiles cause the decay of Tropical Storm Debby (2006) in the numerical simulations. Only with bias correction can data assimilation result in a reasonable portrayal of storm development. Compared with the moisture profiles, temperature profiles show a larger impact on the track forecasting. Assimilation of the temperature profiles resulted in significant improvements in the track forecasts for both Debby (2006) and Typhoon Jangmi (2008).

(3) *How vertical wind shear affects Typhoon Jangmi's rapid intensification*
High-resolution (3-km) numerical simulation of Typhoon Jangmi (2008) was achieved by a nested-grid technique with the WRF model for the period of 12 UTC 24 September through 06 UTC 28 September 2008. During the time period, Jangmi experienced a rapid intensification and two intensity changes. First of all, sensitivity of numerical simulation of Typhoon Jangmi to various microphysics and cumulus schemes in the WRF model was examined. It was found that the simulated intensity of Typhoon Jangmi is very sensitive to the choice of the microphysics schemes. Then, a best set of the numerical simulation (with Lin microphysical scheme) was used to analyze the influence of vertical wind shear to Jangmi's rapid intensification. Two controversial theories (Frank and Retchie 1999 and DeMaria 1996) regarding the role of the vertical wind shear in TC intensity changes were examined: One of the theories describing the impact of shear on intensification states that in high shear environments the upper-level equivalent potential temperature maximum is vented from the cyclone center to the eyewall and the storm's minimum sea-level pressure subsequently rises through hydrostatic adjustment (Frank and Ritchie 1999). Another theory explains shear's impact by emphasizing the accompanying vortex tilt, which, through a thermal adjustment, causes warming near the TC center; this is thought to stabilize the cyclone (DeMaria 1996).

The model simulated storm-averaged wind characteristics are determined and the vertical shear is diagnosed. The sensitive region of equivalent potential temperature impact on minimum sea-level pressure is found to be between 200-300hPa and 30-50km from Jangmi's center, although, notably, the simulated warm core is found to reside below 500hPa. The study finds the venting hypothesis of Frank and Ritchie to be a more accurate way of explaining the shear-intensity relationship during Jangmi's evolution than is the theory of DeMaria. It is found that Jangmi's intensification period ends due to the large gradient that develops between equivalent potential temperature values in the eye and eyewall due to venting; this gradient reduces the lowering of minimum sea-level pressure (MSLP) and stabilizes the eyewall. Importantly, high levels of outward equivalent potential temperature fluxing descend from roughly 100hPa to slightly below 200hPa as the shear increase takes place around 57 hours of the simulation (21 UTC 26 September 2008). This is highly correlated with the end of Jangmi's intensification period. Despite large shear values, there does not appear to be any significant vortex tilt. A likely explanation for this is Jangmi's high penetration depth due to its size, strength, and high latitude at its peak intensity. Notwithstanding, the heating that does occur in the midlevels does not appear to lead to stabilization and weakening.

(4) *The impact of stochastic convection on ensemble forecasts of tropical cyclone development*
Working with Dr. Carolyn Reynolds at NRL, study has been continued on comparing two versions of the NOGAPS ensemble (with and without the addition of stochastic convections) for their abilities in predicting formation, track and development of four typhoons (Nuri, Sinlaku, Hagupit and Jangmi), one tropical storm (Higos) and two non-developing systems (Waves TCS017 and TCS030) during TPARC/TCS-08. It is found that stochastic convection substantially increases the spread in ensemble storm tracks and in the vorticity and height fields in the vicinity of the storm. Stochastic convection also has an impact on the number of ensemble members predicting genesis. One day prior to the system being declared a tropical depression, on average, 31% of the ensemble members predict storm development when the ensemble includes initial perturbations only. When stochastic convection is included, this percentage increases to 50%, but the number of "false alarms" for two non-developing systems also increases. However, the increase in false alarms is smaller than the increase in correct development predictions, indicating that stochastic convection may have potential for improving tropical cyclone forecasting.

(5) *Possible relationships between evolutions of precipitation and TC intensity changes*
In the previous year, the 3-hourly, real-time merged multi-satellite precipitation products from TRMM and TC best track data from the JTWC are used to characterize the evolution of the precipitation features (e.g., the precipitation intensity, distribution and shapes of rainbands) around the core areas of those TPARC/TCS08 TCs during their life cycle (including formation, intensification and dissipating phases). It is found that the rainfall is generally intense during the tropical cyclone formation and intensification but relatively weaker around the TCs' peak intensity. The rainfall structure tends to be more spiral shaped during the TC formation and weakening but becomes more organized during both the TC intensification and mature phases.

Following the progress last year, the evolution of precipitation associated with TC genesis and intensification during August –October over the last 10-year (2000-2009) period are statistically characterized in order to investigate the possible relationships between the precipitation evolutions and TC intensity changes. However, preliminary results show that there were not obvious statistic correlations between intensity of the TCs and maximum precipitation rates. The results seem to be inconsistent with what we found in case studies. Therefore, further investigations are continued in this area.

IMPACT/APPLICATIONS

The development of satellite and radar data assimilation provides significant opportunities to study the environmental conditions of TC genesis, evolution and intensification. The evaluation of the performance of NOGAPS ensemble forecasts of TCs will be helpful for the future development and improvement of ensemble forecast systems.

PUBLICATIONS

(1) Peer-reviewed journal articles

- Thatcher, L. and Z. Pu, 2010: How vertical wind shear affects the rapid intensification of Typhoon Jangmi (2008). To be submitted to *J. Atmos. Sci.*
- Ding, W. and Z. Pu, 2010: Evaluation of a vortex relocation scheme on numerical simulations of tropical cyclones with an advanced research WRF model. To be submitted to *J. Meteorol. Soc. Japan*.
- Zhang L., Z. Pu, W.-C. Lee, and Q. Zhao, 2010: Revisiting the influence of airborne Doppler radar data quality control on numerical simulations of a tropical cyclone. *J. Atmos. Ocean. Tech.* (Submitted).
- Pu, Z., and L. Zhang, 2010: Validation of AIRS temperature and moisture profiles over tropical oceans and their impact on numerical simulations of tropical cyclones, *JGR-Atmosphere* (In press)
- Snyder, A., Z. Pu , and C. A. Reynolds, 2010: Impact of stochastic convection on ensemble forecasts of tropical cyclone development. *Mon. Wea. Rev.,* (In press).
- Snyder, A., Z. Pu and Y. Zhu, 2010: Tracking and verification of East Atlantic tropical cyclone genesis in NCEP global ensemble: Case studies during NASA African monsoon multi-disciplinary analyses. *Wea. Forecasting*, **25**, 1397-1411.

- Pu, Z., L. Zhang and G. D. Emmitt, 2010a: Impact of airborne Doppler wind lidar profiles on numerical simulation of a tropical cyclone. *Geophys. Res. Lett.* **37**, L05801, doi: 10.1029/ 2009GL041765.
- Pu Z., X. Li and J. Sun, 2009: Impact of airborne Doppler radar data assimilation on the numerical simulation of intensity changes of Hurricane Dennis near a landfall. *J. Atmos. Sci.*, **66**, 3351-3365

(2) Students' theses

- Thatcher, L., 2010: How vertical wind shear affects the rapid intensification of Typhoon Jangmi (2008). M. S. Thesis, University of Utah. 170pp.
- Snyder, A., 2009: Tacking and verification of tropical cyclone development in global ensemble prediction systems: Evaluations during recent field programs. M. S. Thesis. University of Utah. 120pp.

(3) *Conference papers and presentations*

- Pu, Z., L. Zhang, Q. Zhao, W.-C. Lee, 2010: Mesoscale numerical simulations of TCS08 typhoons with assimilation of satellite, radar and in-situ observations. *29th Conference on Hurricane and Tropical Meteorology*, 10-14 May 2010, Tucson, AZ
- Ding, W. and Z. Pu, 2010: Evaluation of a vortex relocation scheme and the impact of various synthetic observations on tropical cyclone initialization in an advanced research WRF. *29th Conference on Hurricane and Tropical Meteorology*, 10-14 May 2010, Tucson, AZ
- Zhang, L. and Z. Pu, 2010: A comparison of atmospheric infrared sounder (AIRS) temperature and moisture profiles with dropsonde observations over tropical oceans: the bias correction and impact on numerical simulation of tropical cyclones. *29th Conference on Hurricane and Tropical Meteorology*, 10-14 May 2010, Tucson, AZ
- Thatcher, L., and Z. Pu, 2010: How vertical wind shear affects the rapid intensification of Typhoon Jangmi (2008). *29th Conference on Hurricane and Tropical Meteorology*, 10-14 May 2010, Tucson, AZ
- Pu, Z., L. Zhang, and D. Emmitt, 2010: The impact of airborne Doppler lidar wind measurements on numerical simulations of tropical cyclones. *29th Conference on Hurricane and Tropical Meteorology*, 10-14 May 2010, Tucson, AZ
- Pu, Z., and M. Schroeder, 2010: The relationship between tropical cyclone intensity changes and its precipitation features. *29th Conference on Hurricane and Tropical Meteorology*, 10-14 May 2010, Tucson, AZ
- Pu, Z., L. Thatcher and M. Schroeder, 2009: The Relationship between Tropical Cyclone Intensity Changes and its Precipitation Features. *TCS-08 science team meeting.* October 28-30, 2009 Monterey, CA.
- Snyder, A., Z. Pu and C. Reynolds, 2009: NOGAPS Ensemble Prediction of Tropical Cyclone Genesis: Evaluations during T-PARC/TCS-08. *TCS-08 science team meeting.* October 28-30, 2009 Monterey, CA.
- Pu, Z., L. Zhang and Q. Zhao, 2009: Mesoscale Numerical Simulations of T-PARC/TCS-08 Typhoons with Assimilation of Satellite and Airborne Observations: Predictability Study. *TCS-08 science team meeting*. October 28-30, 2009 Monterey, CA.